Estimating Fuel Channel Bore from Fuel Grab Load Trace Data

C. Berry[1], D. Pattison[1], G.M. West[1], S.D.J. McArthur[1] and A. Rudge[2]

[1]Institute for Energy and Environment, Faculty of Engineering
The University of Strathclyde, Glasgow, G1 1XQ, UK
Email: craig.berry@strath.ac.uk

[2]EDF Energy Nuclear Generation, Barnett Way, Gloucester, UK

Abstract
Detailed measurements of the graphite core fuel channels are made by specialist inspection equipment during planned outages, typically every 18 months to 3 years. Measurement of the bores of the graphite fuel bricks are obtained during these inspections and are used to provide important information about the health of the core. Additionally, less detailed online monitoring data, called the Fuel Grab Load Trace (FGLT) is obtained much more frequently during refuelling events, which can also be used to infer the health of the graphite core. However, this FGLT signal is the result of a number of contributions, where the challenge is to isolate the component associated with the response of the bore from other effects such as gas up thrust. This paper describes the process of creating a model which extracts the isolated component and maps it directly to dimensional measurements of fuel channel bore. The model is created from a combination of the theoretical understanding of the physical interactions of the fuel stringer during refuelling events and several years of refuelling and inspection data, to estimate suitable model parameters. Initially the model created was a coarse estimation of FGLT to fuel bore dimension but through refinements a much more accurate model has been created and demonstrated.

Keywords
Fuel Grab Load Trace, Monitoring, Inspection

INTRODUCTION

The graphite core of an Advanced Gas-cooled Reactor (AGR) is a major life limiting factor for the plant as it cannot be repaired or replaced. There are two ways to obtain information about the condition of the fuel channels inside the graphite core. The first method is through inspection, which occurs every 18 months to 3 years during scheduled outages. This physical inspection is performed either by a Channel Bore Inspection Unit (CBIU) or a New In Core Inspection Equipment mark 2 (NICIE 2) (Cole-Baker & Reed, 2007). The second method is through monitoring data obtained during refuelling events, called the Fuel Grab Load Trace (FGLT). This data measures the perceived weight of the fuel stringer as it is being removed (discharge) and inserted (charge) into the core. FGLTs are required to be recorded and stored by the station for safety purposes as they can be used to detect faults occurring during the refuelling process (West, et al., 2007). However this data can also be exploited to provide health information as fuel channel dimensional change can be observed in the FGLT. Engineers examine the FGLT and look for evidence of anomalous behaviour such as step changes in load between the brick interface peaks, the presence of additional unexpected peaks and changes in the magnitude of the interface peaks. Developing a model that robustly and accurately estimates fuel channel bore given FGLT data would provide operators with additional supporting evidence concerning the health of the core, between planned statutory outages.

This paper will discuss a model that has been created which allows accurate estimations of the dimensions of the fuel channel to be obtained relatively frequently, by using FGLT data. One of the key benefits of this method is that FGLT data is already routinely recorded and stored and therefore no additional equipment or expertise is required to obtain this data. The remainder of this paper will discuss the previous uses of the FGLT data, then proceeds to explain the different components of FGLT data that produce the load value. The iterative process of developing a model is then shown, including testing on a blind dataset.

BACKGROUND

Utilising the FGLT to infer information about the health of the core is an ongoing area of interest, and previous work is reported in West, et al. (2006). A representative average FGLT was generated for each brick layer and the responses of other bricks were compared against this benchmark to identify anomalies. Furthermore, experimental rigs were used to generate responses for various cracked brick configurations and the results were used to provide a means of clustering anomalous brick behaviour. One of the outputs was the construction of a database to store historical and future raw FGLTs as well as additional features about them (West, et al., 2010). These additional features were used to perform automated analysis that aimed to characterise the nature of the bricks, such as the presence of cracks or their identification as narrow bore. Research has also been undertaken to produce estimates of FGLT based on physical understanding and fuel channel dimensions (West, et al., 2014). This process could then be reversed to obtain an approximation for the bore dimensions when provided with the FGLT data.

The novelty in the method of determining core health in this paper is a hybrid of a model-driven and data-driven approach where the data is analysed and backed up with a physical understanding of what impacts the refuelling process. In previous work, FGLT data has been assessed in the context of other complete FGLT signals. In this paper, the explicit relationship between bore and FGLT is being determined through the application of machine learning techniques with an equivalent bore measurement on a one-to-one basis.

FOUR COMPONENTS OF THE FUEL GRAB LOAD TRACE

The fuel grab load trace has previously been represented as a combination of multiple components (West, et al., 2014). This is shown in Equation 1 where the load value at any given point of the FGLT is a function of the location of the height of the lower stabilising brush (LSB) at the base of the fuel stringer. K_L is the parameter that relates the LSB friction to the bore diameter (Φ) at height h. K_U is the parameter that relates the upper stabilising brush (USB) friction to bore at the height ($h + d$) where d is the difference in height between the location of the LSB and the USB. The other contributions to the load are aerodynamic forces from the carbon dioxide coolant (F_G) which are a function of height, and the mass of the fuel stringer (m) which is a constant value for each trace.

$$L(h) = K_L(\Phi(h)) + K_U(\Phi(h+d)) + F_G(h) + m \qquad [1]$$

Approximations to the contributing components of the FGLT can be seen in Figure 1. It should be noted that throughout this paper the load measurements are displayed in mV, based on the data logger, noting that this measurement is directly proportional to load. These approximations have been established through discussions with specialist engineers, theoretical understanding of the components that affect the load, data exploration and understanding of hundreds of FGLTs. Figure 1A shows the expected contribution of the LSB ($K_L(\Phi(h))$). Figure 1B shows the expected contribution of the USB ($K_U(\Phi(h+d))$). The USB sits outside the graphite core and interacts with the guide tube as an interface in two sections. An assumption made here is that the steel section of the guide tube is of constant bore diameter and that it does not distort in the same manner as graphite. Figure 1C is the deadweight of the fuel stringer. Each fuel stringer has a slightly different absolute weight which needs to be estimated on a trace by trace basis. An assumption here is that the deadweight will not alter during the course of refuelling. Figure 1D displays the aerodynamic effects which are the most complex to model and which depend on whether the reactor is online of offline during refuelling. It can be simplified to three regions; an in core region, an out of core region and a transitional region between the two. Exploration of the information arising from the stabilising brushes is now discussed.

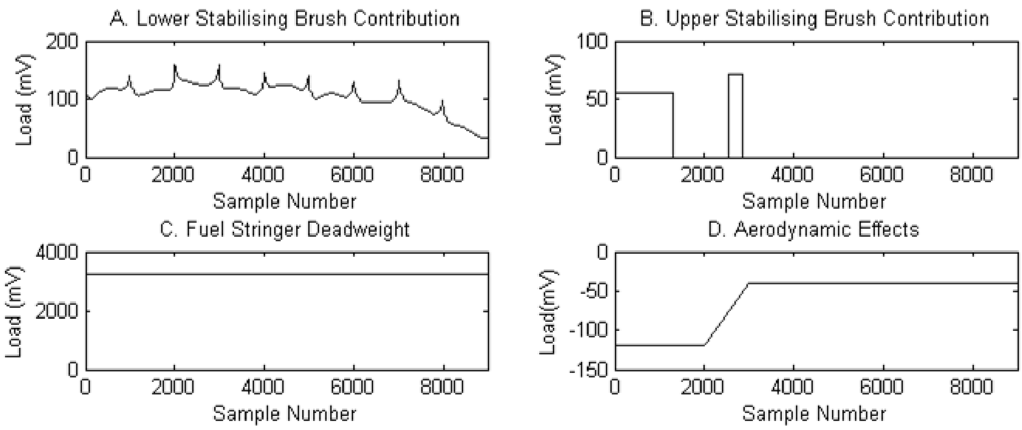

FIGURE 1: Approximations of the values of each of the four components that contribute to the load value of the FGLT

Lower Stabilising Brush Analysis

LSB friction component analysis was performed on brick layers 6-11 and only on the traces which were obtained during offload depressurised refuelling from Hunterston B. The assumption is that in these regions, if the deadweight value of the fuel stringer is removed then there is only LSB frictional forces left. Brick layers below layer 6 were intentionally not included at this stage as they contain regions with both LSB and USB friction contribution. The aim of the data analysis is to determine the relationship between load and bore from the available refuelling data. The data was then visualised on a scatter graph against the corresponding bore values from inspection data that was obtained within the same refuelling period as seen in Figure 2.

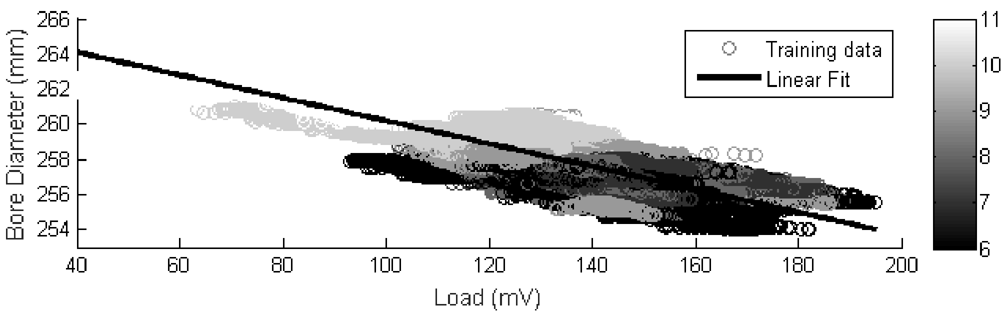

FIGURE 2: Scatter plot and linear fit of the load to bore relationship from offload refuelling data. The grayscale intensity of the training data indicates from which brick layer the data was obtained.

Rig work has been performed to allow the relationship of load to bore to be calculated between diameters of 251-263mm in machined graphite bricks (Skelton, 2007). It was found that a cubic polynomial best described this relationship. From the CBIU/NICIE 2 data the range obtained was roughly 254-263mm and as a first step a linear rather than cubic approximation was made. This linear assumption could change if more refuelling data is obtained that has narrower bore measurements and supports a non-linearity.

Upper Stabilising Brush Analysis

Before beginning to analyse the data for the USB regions, the physical understanding of the USB interactions was that they would affect the load value by introducing a step change in load in those regions. There are three main sections in the FGLT which have contributions from the USB. These occur where the diameter at the location of the USB is narrower than 250mm. The first region is from the start of the trace until the LSB enters brick layer 4, this is when the USB is in the narrow section of the guide tube of the refuelling machine, which only has a diameter of 248.2mm. The second USB region occurs when the LSB is in brick layer 5 and this is due to the piston seal bore which has a diameter of 247.65 mm. The last region is when the LSB is midway through brick layer 9, but this region is not present in every trace. This is due to the USB "hunting" for the entrance to the standpipe. The reason this may not be present in every trace is that it is wider than the USB with a diameter of 250.4 mm and that it only occurs when they are not aligned well.

The data exploration that was performed aimed to confirm that the USB friction force applies a constant offset to the load value in those regions. The brick layer 5 interaction, which contains the piston seal bore, was investigated by calculating the difference in the load value caused by the USB interaction. It was found that the USB contribution was nearly constant for both the onload and offload traces with an offset of between 60 and 100mV. The variations found in these values are assumed at this stage to be produced by the LSB frictional components not being constant throughout the USB region.

MODEL DESCRIPTIONS

Initial Bore Estimation Model

The initial predictive model that was created was trained based on the previous conclusion that for the range of data that was investigated the relationship of load to bore is linear. Initially the deadweight analysis is performed on the trace to identify the deadweight value of the fuel stringer in this particular refuelling event and remove that value from the rest of the trace. Based on the assumptions made about the FGLT this means that for offload depressurised traces, assuming that aerodynamic effects are negligible, there are now only contributions for the LSB present in the trace. In the first model the linear relationship was trained on a single brick's discharge LSB relationship to the bore, assuming that this brick was representative to all bricks in the core. The brick that was chosen was from layer 10 and a linear relationship was trained. The result can be seen in Equation 2, where Φ is the bore in mm at a specific height, h, in the core. K_L is a linear function that relates load to bore, L is the load in mV, m is the deadweight in mV and c is an offset learned from the layer 10 training data. To use this initial linear regression model the input data was pre-processed to remove the effects of the brick interfaces which introduce an unwanted dynamic transient. When this was then applied to the test set it was found that each brick had a constant offset over the entire brick compared with the true value, this constant offset was different for each brick. Initially with a smaller amount of data that was available an explanation was found where the required unknown offset was found to be linearly related to the difference in the average load of the brick that is being predicted and the original brick from layer 10 that was used to train the first linear regression model. Therefore a second linear regression model was used to learn this relationship.

$$\Phi(h) = K_L(L(h) - m) + c \qquad [2]$$

This model included the layers in the FGLT data that contained the USB contributions but however did not make any attempt to remove them and instead included those layers within the second linear regression model. Therefore results that are obtained from brick layers below layer 6 are not as reliable. The USB friction contribution regions are treated as if they are separate brick layers for calculating the required offset. The equation for the initial model is shown in Equation 3, where the learned offset, c, from Equation 2 is replaced by K_O. $K_{O\ is}$ the second linear regression function that calculates the required offset over an entire brick layer (BL) based on the average load value of that brick layer.

$$\Phi(h) = K_L(L(h) - m) + K_O(BL, L(BL)) \qquad [3]$$

Second Bore Estimation Model

While developing the second model the initial bore linear regression model was discarded and the required constant offset from each brick layer was investigated further. In addition while focusing on the best way to incorporate the unknown residual effects, the model focussed only on the regions which did not include USB friction which are the brick layers 6-11. Similarly to the initial model the deadweight for each trace is calculated and removed from the trace. Again a linear regression model is used to train the initial load to bore relationship. However instead of being trained on a single brick the relationship is trained on all of the available bricks to create a global regression model. This second linear regression model is not applied on a per layer basis and instead is applied to the entire trace similar to the first linear regression. The relationship of the second linear regression was established by choosing a data point at the end of brick layer 10 and normalising every trace to that point. It found that from layer 10 downwards there was a gradual increase in the prediction error that was a linear relationship. The second linear regression is necessary as although the trace is a depressurized offload trace there is still some residual gas flow. This provides a different contribution to the load value based on the height of the fuel stringer in the core.

A limitation with this method is that there is an underlying offset required to understand this second residual model that requires the bore estimation produced from the first linear regression model to be correct at the upper end of brick layer 10 and if this is not the case needs to be corrected. The solution was to use the last previously known value of the bore at this location as it is in a region that does not vary as much as the other regions of the core. However this then means that if that value is unknown the model is now only providing a relative estimation of the bore to the value at the upper end of brick layer 10. The equation for the second model is shown in Equation 4, where Φ is the bore in mm for a specific height, h, in the core. K_L is a linear function that relates load to bore, L is the load in mV, m is the deadweight in mV, K_O is the second linear regression function and H_O is the required offset to normalise the bore to the end of brick layer 10.

$$\Phi(h) = \quad K_L(L(h) - m) + K_O(h) + H_O \qquad [4]$$

Third Bore Estimation Model

The third model which has been implemented improves the accuracy of predicting the unknown offset and also reintroduces an attempt to predict the brick layers which contain USB friction components. However, unlike the first two models this model did not remove the deadweight value that had been calculated for each trace. It was found that for some traces, due to the presence of unknown aerodynamic forces, that removing the deadweight as an offset would increase the variance in the load to bore relationship. The linear regression model was kept as it still remained the most representative to the historical refuelling data. As with the second model the linear regression model was trained on randomly selected standard bricks.

Similarly to the second model this estimation of fuel channel bore is a relative measure rather than an absolute measure as it estimates how different the bore values are from the top end of brick 10 in the channel. However with the inclusion of the lower brick layers 3-5, which contain USB friction, it was found that the second linear relationship should actually be a non-linear relationship. A polynomial model was used to fit the residual gas effects including layers 3-5 and the residual offset becomes non-linear. Provided the offset is due to gas flows this is due to the transition of the fuel stringer from inside the core region to outside it.

The USB is able to be removed from the trace by detecting a step change in the load value of the FGLT. Based on the analysis of the USB regions it was believed that their contribution to the load value is a constant when they are present, meaning that the step change in load can be calculated and removed from those regions. This introduces a slight error at the interface of the USB regions as there is a transient response between the different load values that is difficult to identify and remove completely. It is assumed that the removal of the USB does not affect the contribution to the load value from the LSB in these regions. The equation for the third model is shown in Equation 5, where Φ is the bore in mm for a specific height, h, in the core. K_L is a linear function that relates load to bore, L is the load at a specific height, K_U is the required offset to remove the USB interaction at a specific height, K_O is the second polynomial regression function at a specific height and H_O is the required offset to normalise the bore to the end of brick layer 10.

$$\Phi(h) = K_L\big(L(h) - K_U(h)\big) + K_O(h) + H_O \qquad [5]$$

RESULTS

All three models were tested on unbiased FGLT traces which were not used in the training process of the models. The initial model was trained on 10 traces whereas the second and third models were trained on 30 random traces each. This increase in training traces was due to more data from outages becoming available between the generation of the initial model and the later models. All three of the models were then evaluated on the same 10 traces to estimate their channel bore. An example of the estimations of one of the traces is shown in Figure 3 where the three estimations are shown with the actual bore measurements obtained from CBIU/NICIE 2 equipment. It can be seen for this trace that the third model performs much better and more consistently over the entire trace for estimation. It can be seen that the second and the third model are very similar in the upper brick regions. This is because in the upper brick layers the second regression for the offset are very similar but the second model's linear relationship would not be suitable for brick layers less than 6.

Visual inspection of the results, such as those shown in Figure 3, show that there appears to be improvements as each of the models is developed. The statistical properties are shown on a per brick layer basis for RMSE and maximum error (in mm) in Table 1 and Table 2 respectively. Comparing the global statistical properties of the data makes it difficult to see improvements as each model covers different percentages of the core. For example, regions of the trace are ignored in brick layers 4 and 5 for the initial model due to the transient regions that occur around the USB interacting sections. These regions however are estimated in the third model by attempting to detect and remove the USB contribution from the trace which has increased the RMSE of the entire trace but have allowed greater regions of the bricks to be modelled compared to the initial model. The true improvement of the second and third models can be seen in their upper brick regions specifically brick layers 7-10, where the RMSE and maximum errors are lower than in model 1. It is important to note that the third model has complete coverage of the middle of the bricks for brick layers 3-11 with only the areas around the brick interfaces not being estimated. The desired properties of a final model would be to be able to achieve an accurate estimation of bore, so that for any point in the trace the residual is less that ±1mm. This goal is being improved upon with the third model for the upper brick layers which all have a smaller maximum error than the first model.

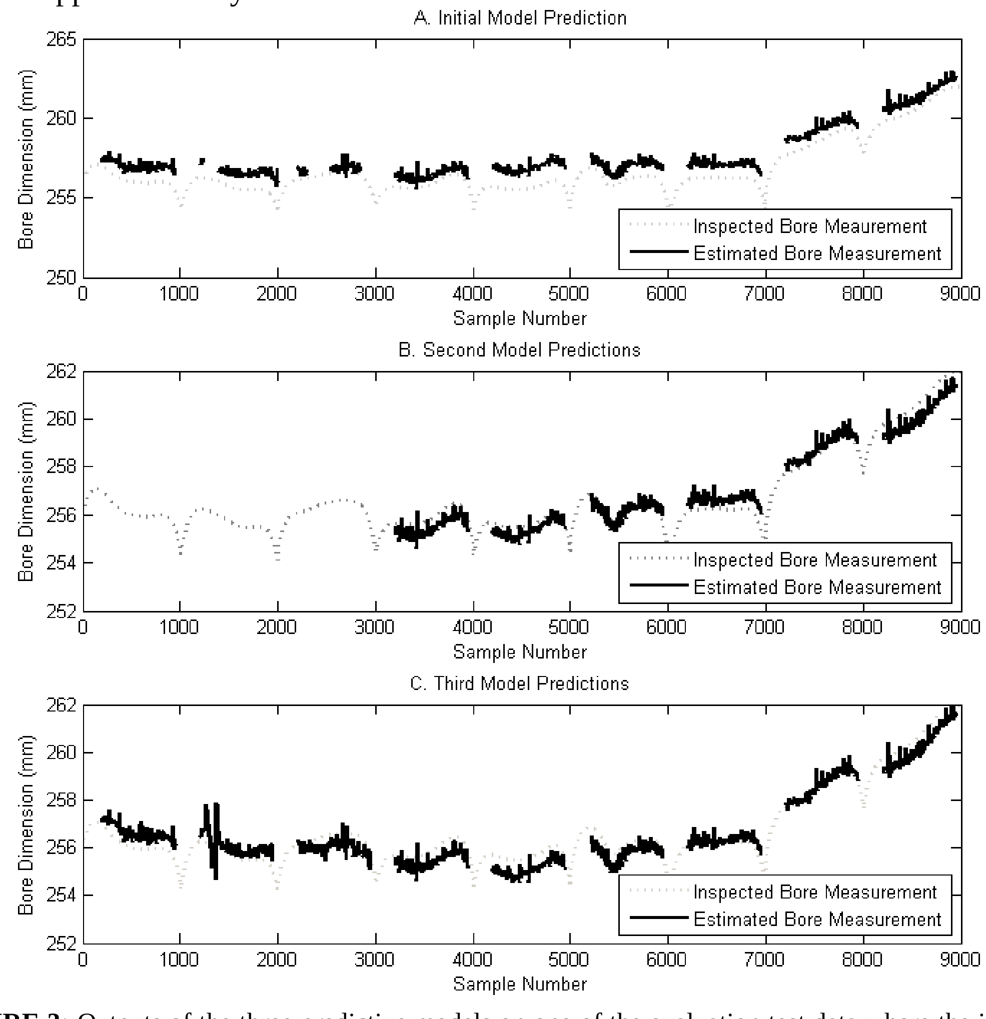

FIGURE 3: Outputs of the three predictive models on one of the evaluation test data where the inspection data is gray dotted line and the estimations are the solid black line. It can be seen that through the progression of the models that the accuracy has increased on this trace.

TABLE 1: The root mean square error (mm) on a per brick layer basis for the 10 evaluation test data traces.

	BL 3	BL 4	BL 5	BL 6	BL 7	BL 8	BL 9	BL 10	BL 11
Model 1	0.698	0.987	0.563	0.472	0.935	0.443	0.588	0.371	0.424
Model 2	N/A	N/A	N/A	0.562	0.720	0.342	0.491	0.288	0.567
Model 3	1.08	0.937	0.516	0.555	0.730	0.379	0.423	0.291	0.458

TABLE 2: The maximum error (mm) on a per brick layer basis for the 10 evaluation test data traces.

	BL 3	BL 4	BL 5	BL 6	BL 7	BL 8	BL 9	BL 10	BL 11
Model 1	3.00	4.27	5.37	1.63	2.88	1.43	1.64	1.58	1.91
Model 2	N/A	N/A	N/A	1.36	2.15	1.19	1.60	1.42	1.39
Model 3	2.69	5.99	2.21	1.63	2.07	1.25	1.44	1.39	1.51

CONCLUSIONS AND FUTURE WORK

It has been shown how the various components of the fuel grab load trace can be removed to leave the contribution from the lower stabilising brush, which in turn can be used as an input to determine the bore of the graphite bricks throughout the channel.

The predictive model has been iteratively improved throughout multiple models showing an overall improvement on accuracy and reduction of error. Through the improvements in the model the accuracy has increased in the upper core regions especially brick layers 7-10. The other main improvement of the model is the larger area of the fuel channel being estimated which includes previously neglected regions in the earlier models. It is intended that eventually a finalised predictive model will be able to be utilised as a decision support tool to assist in ensuring the safe operation of AGRs. Improvements that will be made in the future include less reliance on relative predictions, the incorporation of charge traces and investigation of non-linear relationships for the LSB load to bore relationship.

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